BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B70 07037

SUBJECT: Flight Performance of Apollo Cryogenic Oxygen System Case 320

DATE: July 13, 1970

FROM: R. V. Sperry

ABSTRACT

Performance data on the Apollo cryogenic oxygen system from several missions have been analyzed to examine repressurization time and heat input as functions of oxygen quantity in the tank. These are compared with predicted characteristics contained in the Apollo Operations Handbook and in the Systems Data Book.

Measured repressurization time is generally about twice the predicted time, even after long periods without fan operation. This is especially surprising since stratification would be expected to shorten the repressurization cycle by localizing the heating.

Energy supplied to the tank is generally about twice the predicted value for the observed delivery rate, if computed on the assumption that heater operation is continuous during each pressurization cycle. The comparison between measured and predicted energy is reasonably close for Tank 2 on the Apollo 11 mission, which had only one of its heaters in operation.

The discrepancy implies that more than predicted energy is leaving the tank, and/or that less than the assumed energy is being delivered to the tank. Delivery of oxygen from the tank at higher than the bulk material temperature will cause a discrepancy in the observed direction, but unreasonably high temperature differentials are necessary to account for the magnitude of the discrepancy. Operation of the heaters on a partial duty cycle due to action of thermostatic switches would deliver less energy than the assumed continuous operation. Simple thermal calculations suggest that in an unstirred tank, the heater assembly should reach the thermostat operating point (≈ 80°F) in a few minutes, and would thereafter cycle rapidly between its opening and closing states. It is therefore proposed that telemetry data from previous Apollo missions be examined carefully to see if the spacecraft current and voltage profiles show any evidence that individual heaters are cycled by thermostats during the pressurization periods.

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MEMORANDUM FOR FILE

Flight data from the cryogenic oxygen system on the Apollo 8, 9, 11, and 12 missions* have been compared with predicted characteristics contained in the Apollo Operations Handbook (AOH) and the Systems Data Book (SDB), to examine repressurization time and heat input as functions of oxygen quantity in that tank.

The Apollo Operations Handbook page 2.6-17 (Fig. 1) shows predicted oxygen tank repressurization time as a function of oxygen quantity in the tank. The predicted pressurization time T_1 is based on the following assumptions:

$\dot{\omega}_1$ (oxygen delivery rate) = 1 lb/hr

Δp_1 (pressure change) = 70 psia

H_1 (total heat input rate) = 595.87 BTU/HR

Heaters	389.67	BTU
Fans	180.2	BTU
Heat leak	26.0	BTU
Total	595.87	BTU

In the actual missions these factors had different values, and it was therefore necessary to apply corrections to the predictions and flight data to permit valid comparisons.

New repressurization time predictions T_2 were computed for each mission, using

$\dot{\omega}_2$ = average delivery rate for mission

Δp_1 = 70 psia

H_2 = 389.67 BTU/HR (Heaters) + 26 BTU/HR (Heat leak)

= 415.67 BTU/HR

* From telemetry data and Beech Aircraft Corporation reports.

and letting $T_2 = T_1 \dfrac{H_1 - \dot{\omega}_1 F_1}{H_2 - \dot{\omega}_2 F_1}$,

where F_1 = BTU/HR for delivery of 1 lb/hour for the applicable tank quantity as determined from page 4.1-17 of the Systems Data Book (Fig. 2).

The pressure change associated with repressurization cycles in flight was found to be variable. It was impracticable to correct the predictions for this, and therefore the repressurization times measured from flight data were extrapolated to a Δp = 70 psia by multiplying each data point by the ratio:

$$\frac{70 \text{ psia}}{\text{actual } \Delta p} .$$

Modified predictions and flight data from Apollo 8, 9, 11, and 12 are shown in Figures 3 through 7. While the flight data exhibit considerable variability, the repressurization times are generally around twice the predicted times. The agreement is much closer for Apollo 8 and for Tank 2 on Apollo 11. No difference is known for Apollo 8, however, Tank 2 on Apollo 11 had only one of its two heaters in operation. As stratification should cause shorter than predicted repressurization times, it is especially surprising to find the opposite trend.

Figure 2 from the Systems Data Book shows the heater and fan duty cycle required for various oxygen delivery rates, as a function of oxygen quantity in the tank. These assume an electrical input of 166.8 watts or 569 BTU/HR from heaters plus fans. Thus 569 multiplied by the duty cycle expresses the average energy requirements (in addition to the heat leak) in BTU/HR rather than in duty cycle for the corresponding flow rate and oxygen quantity in the tank.

Figures 8 through 12 show for each mission the predicted heat input (in addition to the 26 BTU/HR heat leak) for the average oxygen delivery rate of that mission, and the measured data points. The latter assume that the heaters are on continuously during each repressurization period, and that no heat is provided by the fans. The heat input (in addition to the heat leak) is therefore computed as:

$$(\text{Heater input} \times \text{duty cycle}) =$$

$$\left(389.67 \text{ BTU/HR} \times \frac{\text{on Time}}{\text{Total Time}}\right)$$

The flight data show that the energy supplied to the tank is generally about twice the predicted value for the observed delivery rate, if computed on the assumption that heater operation is continuous during each pressurization cycle. The comparison between predicted and measured energy is reasonably close only for Tank 2 on the Apollo 11 mission, which had only one of its two heaters in operation.

The observed discrepancies imply that more than the predicted energy is leaving the tank and/or that less than the assumed energy is being delivered to the tank. Delivery of oxygen from the tank at higher than the bulk material temperature could cause a discrepancy in the observed direction. For all missions a discrepancy of 17 degrees in the required direction has been observed between the measured temperature and that calculated from the pressure and quantity measurements. Using Apollo 12 as an example the required increase in exhaust fluid temperature and the associated potential pressure collapse were computed and plotted on Figure 13. For tank quantities greater than 60% the excess temperature is considerably greater than 17 degrees and unreasonably high for quantities greater than 70%. In all cases the computed pressure collapse was much greater than observed. In fact for quantities greater than 60% a two phase condition would be reached.

Operation of heaters on a partial duty cycle due to action of thermostatic switches would deliver less energy than the assumed continuous operation. Figure 14 shows the calculated thermal response of the heater assembly under conditions which might apply in an unstirred tank in zero gravity. This suggests that in an unstirred tank, the heater assembly should reach the thermostat operating point (+ 80°F) in a few minutes and thereafter cycle rapidly between its opening and closing limits. Tank 2 on the Apollo 11 mission, with only one heater in operation, would be expected to have a higher heater duty cycle, and its calculated heat input is indeed found to be closer to prediction.

The indications from this data review have been discussed with the concerned engineers at MSC, and arrangements are being made to examine telemetry records of the spacecraft electrical power system to see if there is any indication that individual heater thermostatic switches are cycling in flight.

R. V. Sperry

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2031-RVS-ep

Attachments

SYSTEMS DATA

Quantity (percent)	Oxygen		Hydrogen	
	Repressurization Time (minutes)* (865 to 935 psia)	Flow at 965 psia	Repressurization Time (minutes) (225 to 260 psia)	Flow at 225 psia
100	4.0	3.56	20.0	0.38
95	4.3	3.97	21.0	0.42
90	4.6	4.55	22.0	0.46
85	5.0	5.27	23.0	0.49
80	5.4	6.02	24.5	0.52
75	5.7	7.01	26.5	0.65
70	6.5	7.94	28.5	0.76
65	7.4	9.01	31.0	0.80
60	8.7	10.80	33.5	0.87
55	9.6	12.54	36.0	0.93
50	10.8	14.19	39.0	0.97
45	11.5	15.69	41.0	0.98
40	12.4	17.01	41.0	0.97
35	12.6	17.56	41.0	0.94
30	13.0	17.56	40.5	0.91
25	13.1	16.55	40.5	0.83
20	13.2	15.48	42.0	0.71
15	14.5	12.28	47.0	0.54
10	17.8	8.76	58.0	0.37
7.5	21.4	7.09	71.0	0.23
5	24.0	5.37	Continuous	0.16

To avoid excessive temperatures, which could be realized during continuous heater and fan operation at extremely low quantity levels, a thermal sensitive interlock device is in series with each heater element. The device automatically opens the heater circuits when internal tank shell temperatures reach +90°F, and closes the circuits at +70°F. Assuming normal consumption, oxygen temperature will be approximately -157°F at mission termination, while hydrogen temperature will be approximately -385°F.

The manual mode of operation bypasses the pressure switches, and supplies power directly to the heaters and/or fans through the individual control switches. It can be used in case of automatic control failure, heater failure, or fan failure.

Tank pressures and quantities are monitored on meters located on MDC-2. The caution and warning system (CRYO PRESS) will alarm when oxygen pressure in either tank exceeds 950 psia or falls below 800 psia. The hydrogen system alarms above 270 psia and below 220 psia. Since a common lamp is provided, reference must be made to the individual pressure and quantity meters (MDC-2) to determine the malfunctioning tank. Tank pressures, quantities, and reactant temperatures of each tank are telemetered to MSFN.

Oxygen relief valves vent at a pressure between 983 and 1010 psig and reseat at 965 psig minimum. Hydrogen relief valves vent at a pressure between 273 and 285 psig, and reseat at 268 psig minimum. Full flow venting occurs approximately 2 pounds above relief valve opening pressure.

*BASED ON 1 LB/HR DELIVERY

FIGURE 1

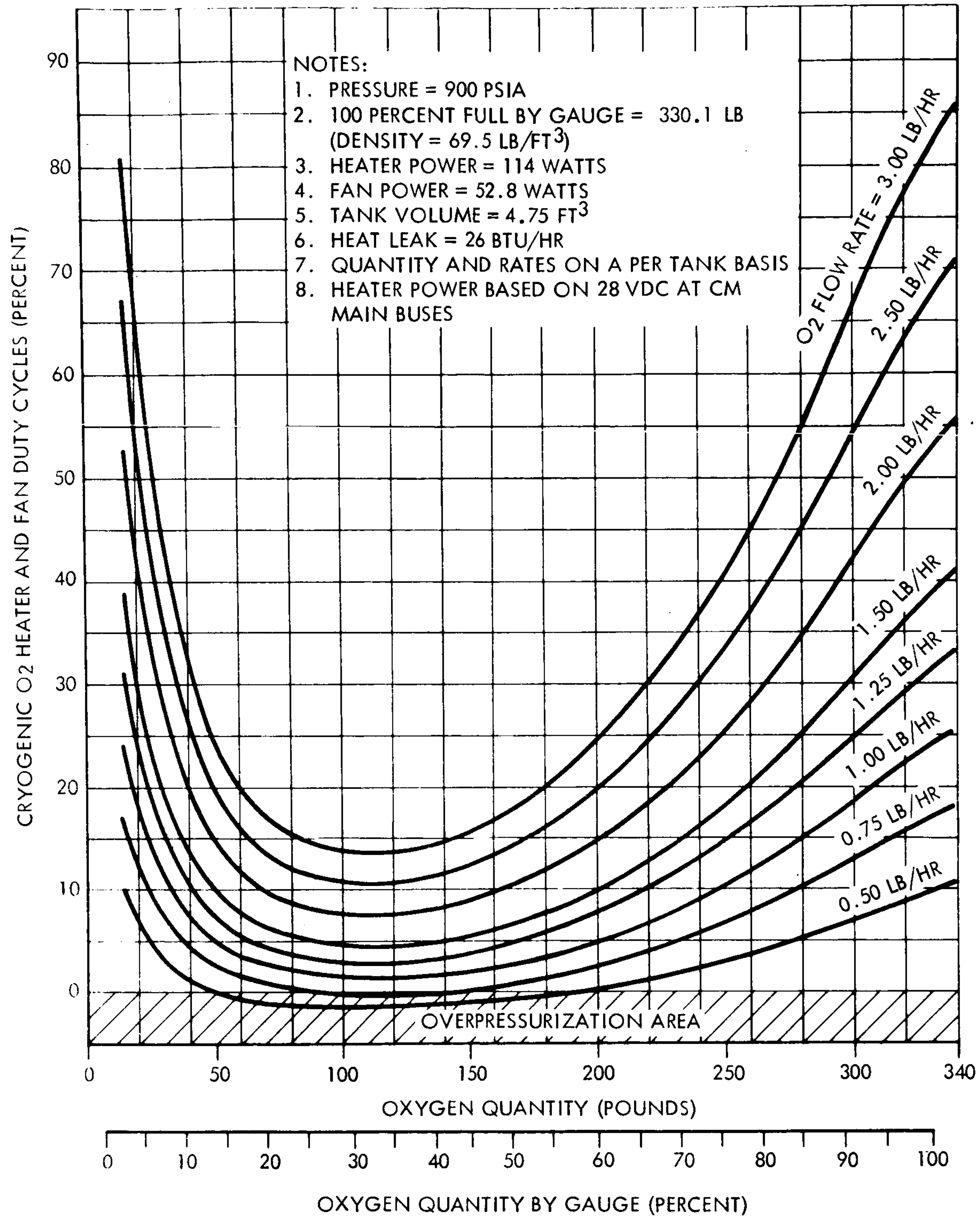
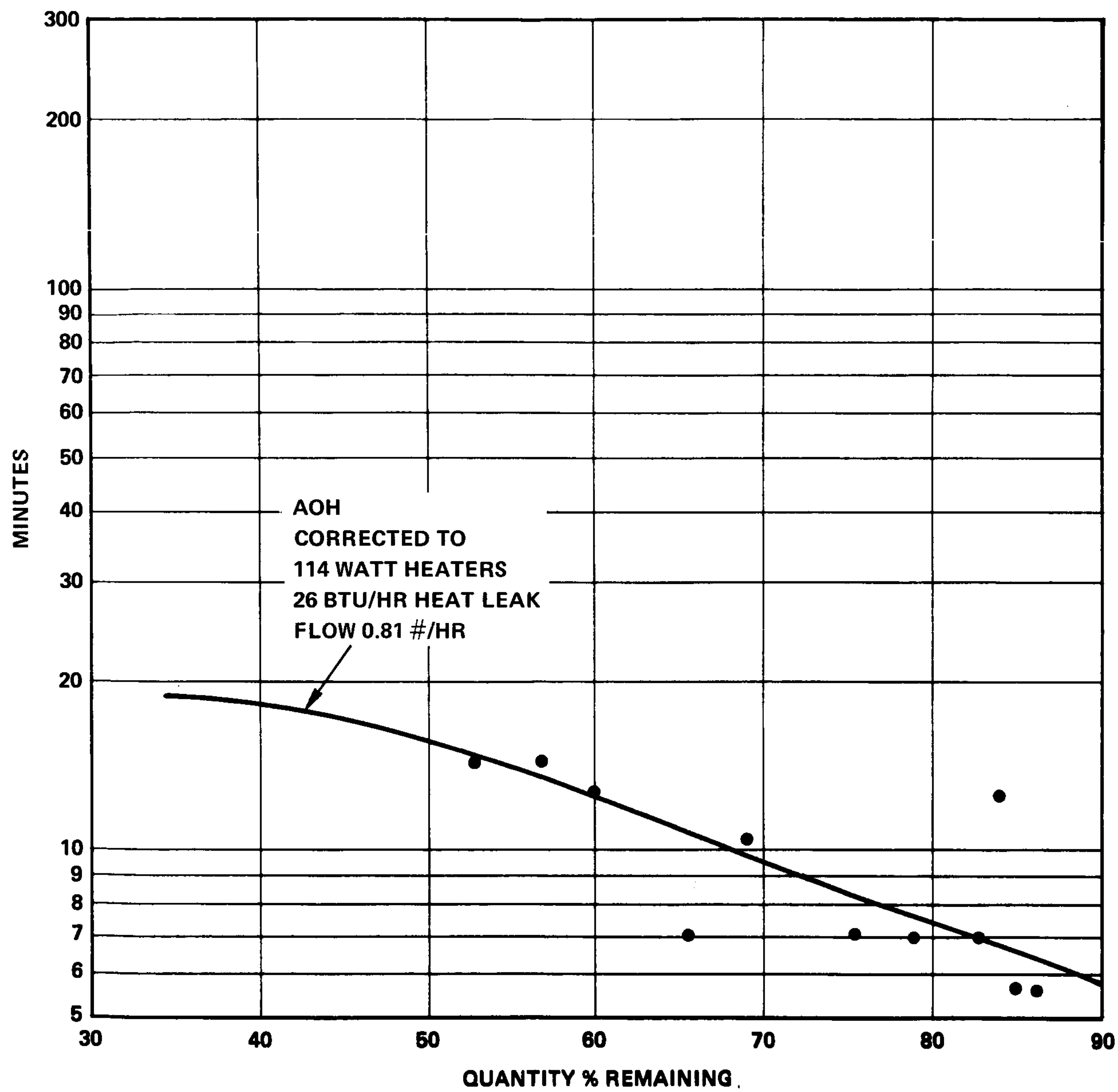


Figure 4.1-2. Cryogenic O_2 Heater and Fan Electrical Duty Cycles Versus O_2 Quantity and Flow Rate for One O_2 Tank

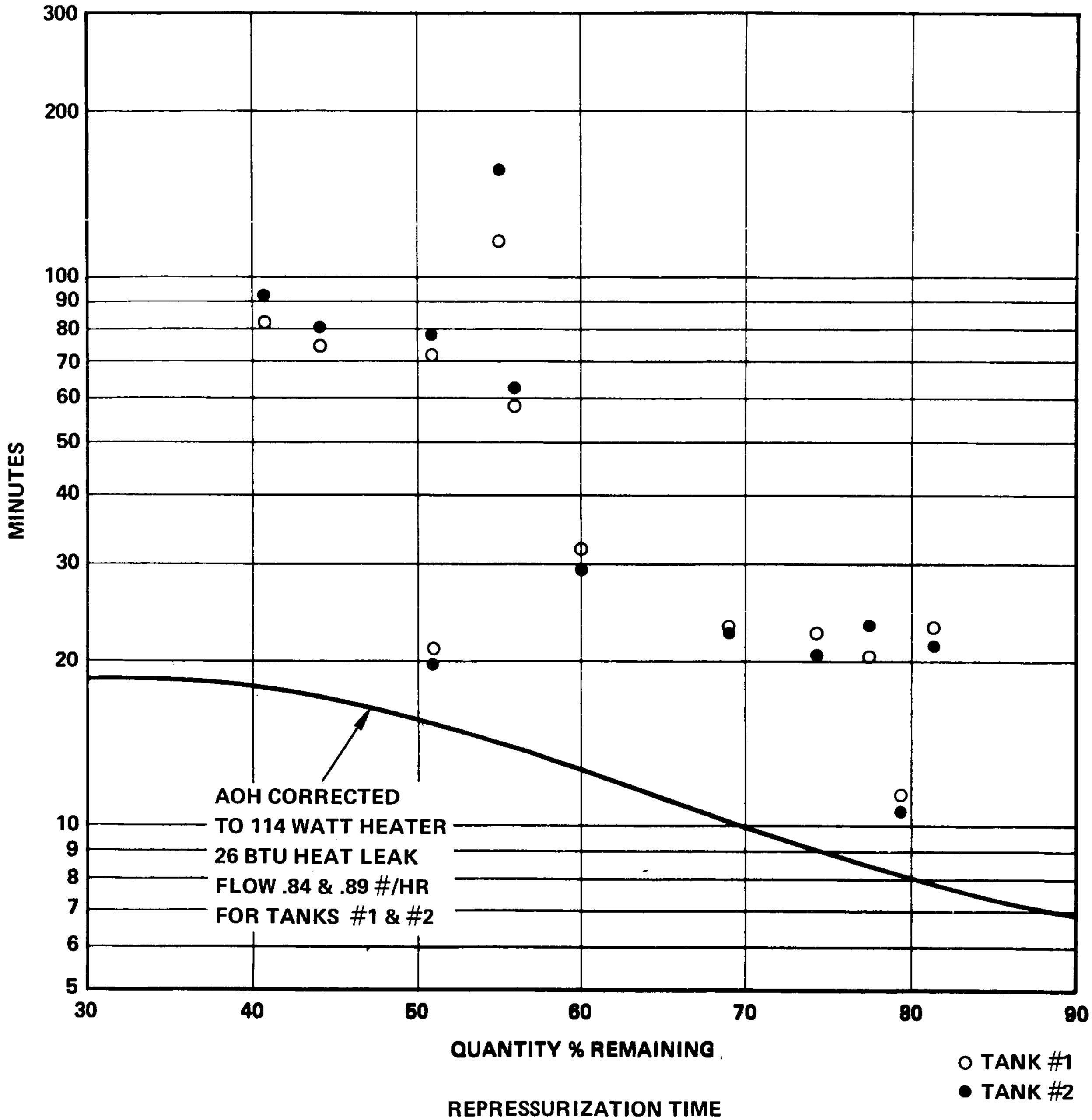
FIGURE 2



REPRESSURIZATION TIME
APOLLO 8 O_2 TANKS

(CORRECTED TO $\Delta P = 70$ PSI)

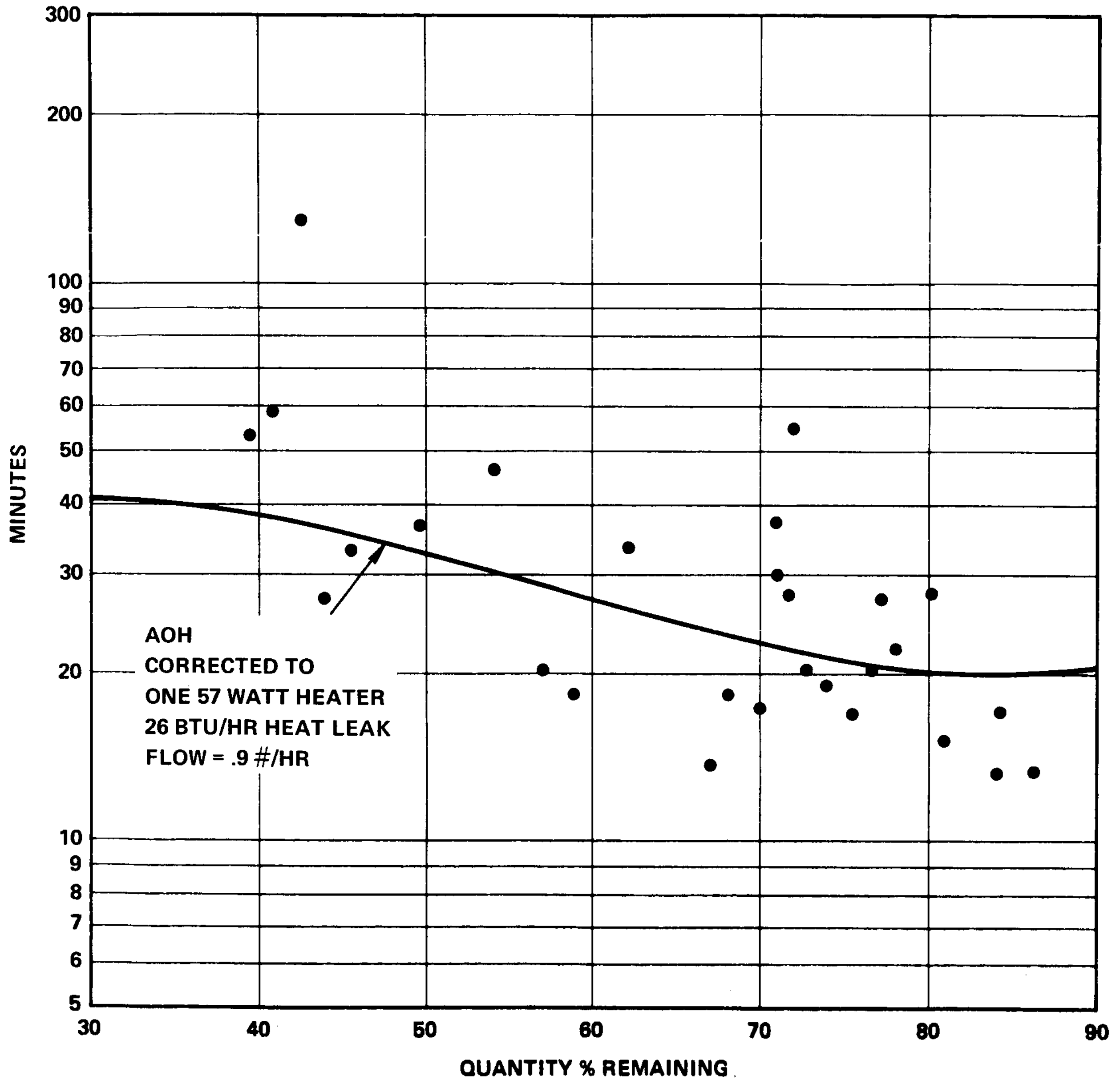
FIGURE 3



REPRESSURIZATION TIME
APOLLO 9 O_2 TANKS

(CORRECTED TO ΔP = 70 PSI)

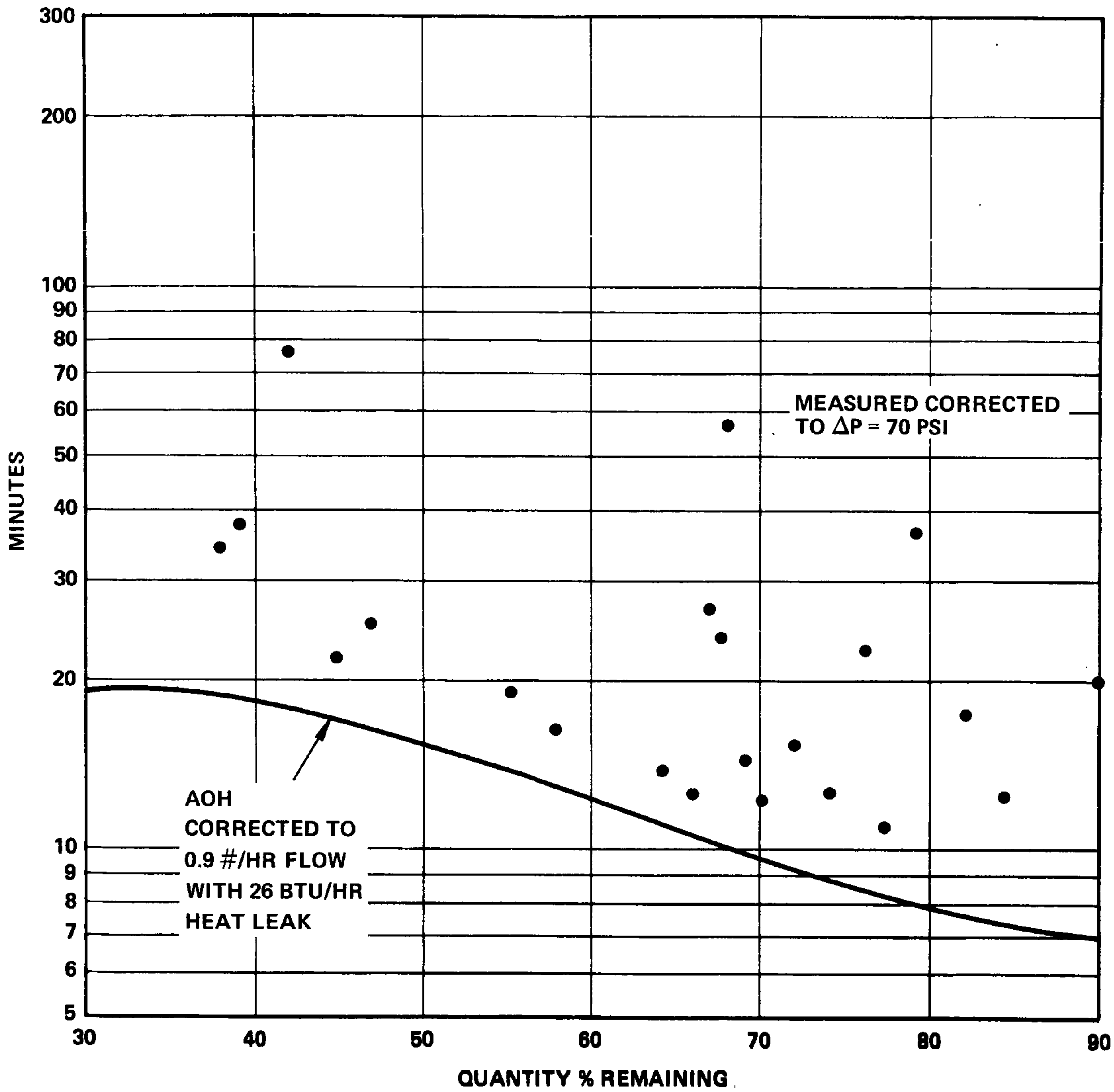
FIGURE 4



REPRESSURIZATION TIME
APOLLO 11 O_2 TANK 2

(CORRECTED TO ΔP = 70PSI)
(ONE HEATER FAILED)

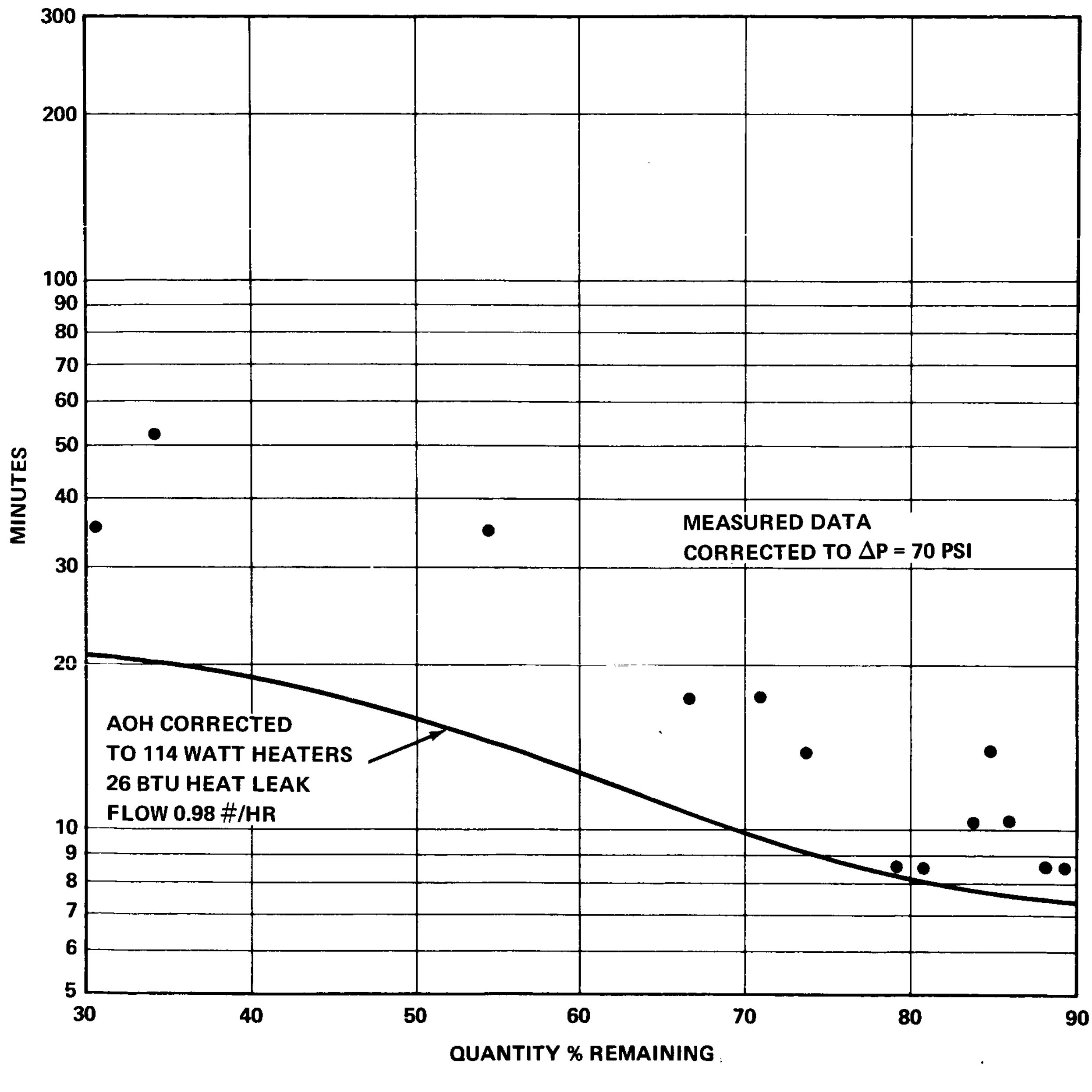
FIGURE 5



REPRESSURIZATION TIME

APOLLO 11 O_2 TANK 1

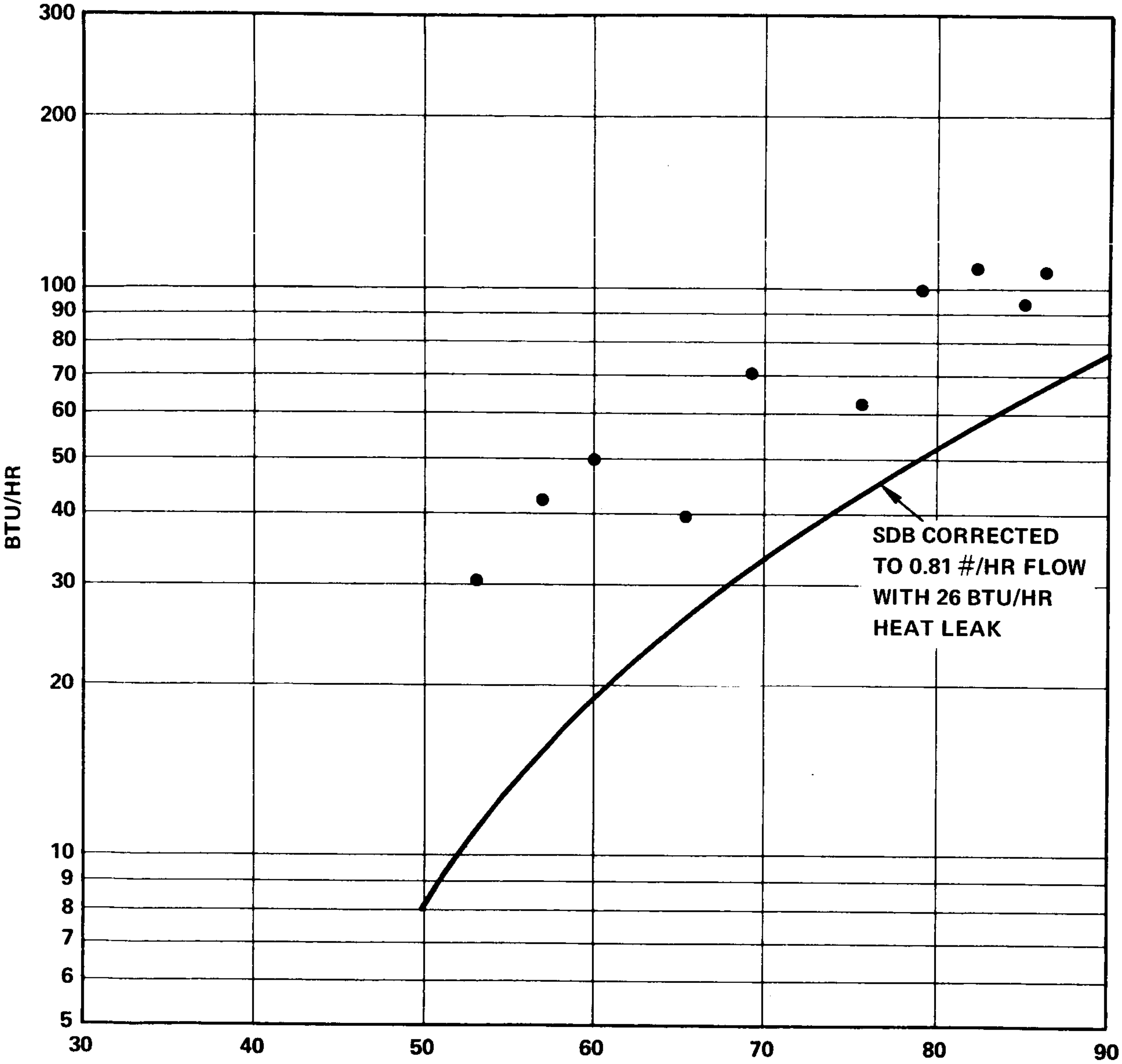
FIGURE 6



REPRESSURIZATION TIME
APOLLO 12 O_2 TANKS

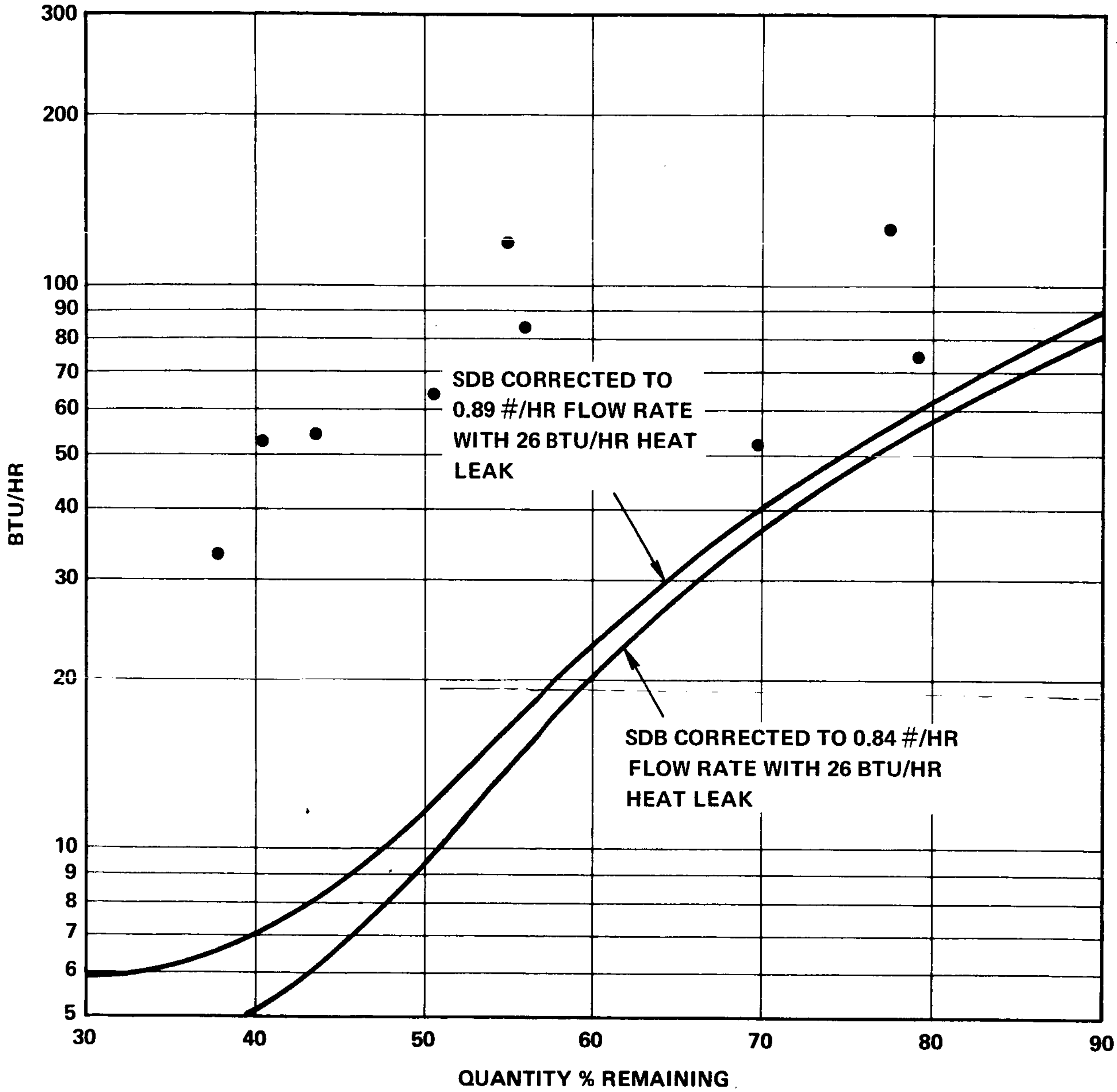
(CORRECTED TO ΔP = 70 PSI)

FIGURE 7



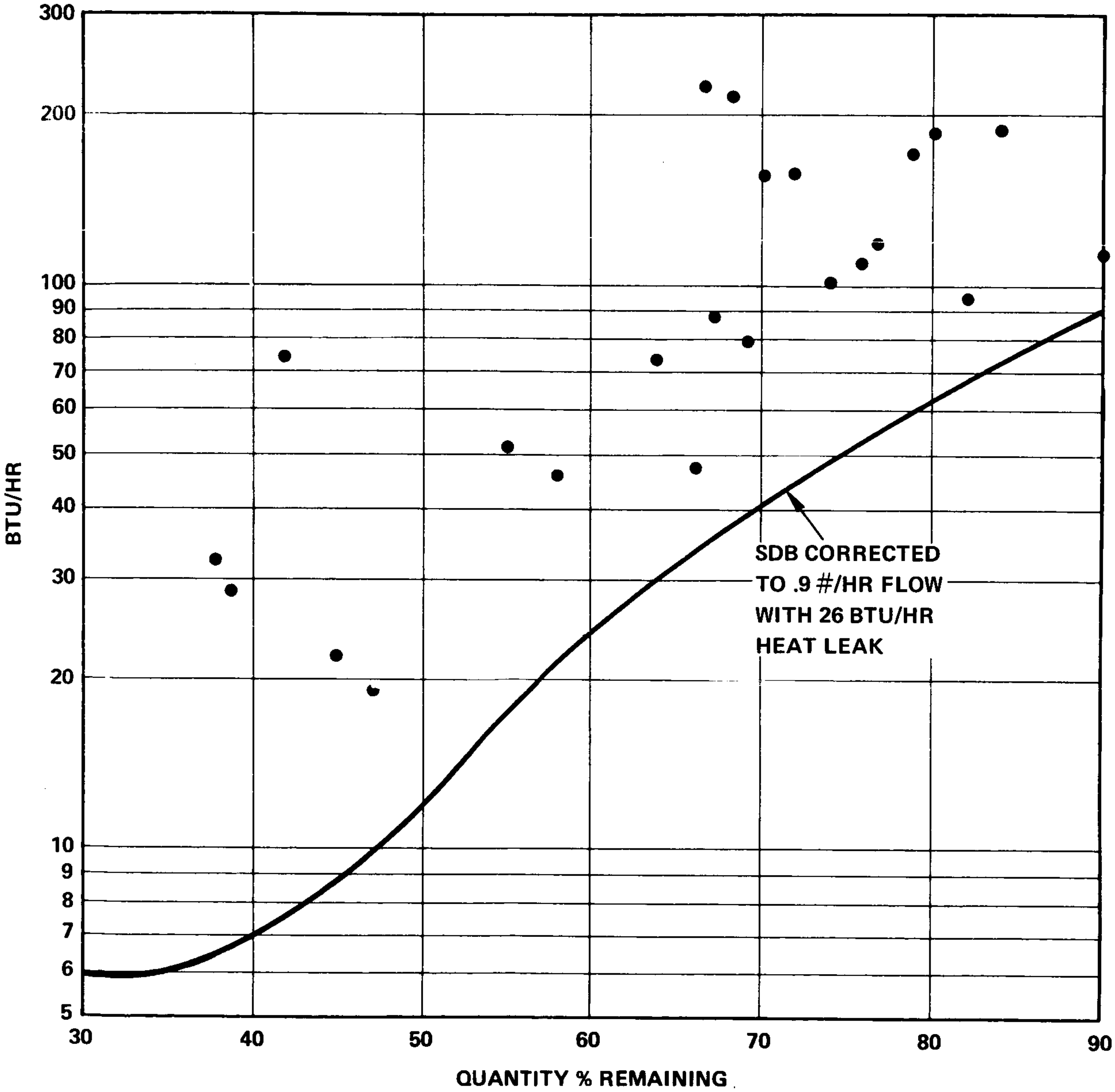
AVERAGE HEAT INPUT
APOLLO 8 O_2 TANKS

FIGURE 8



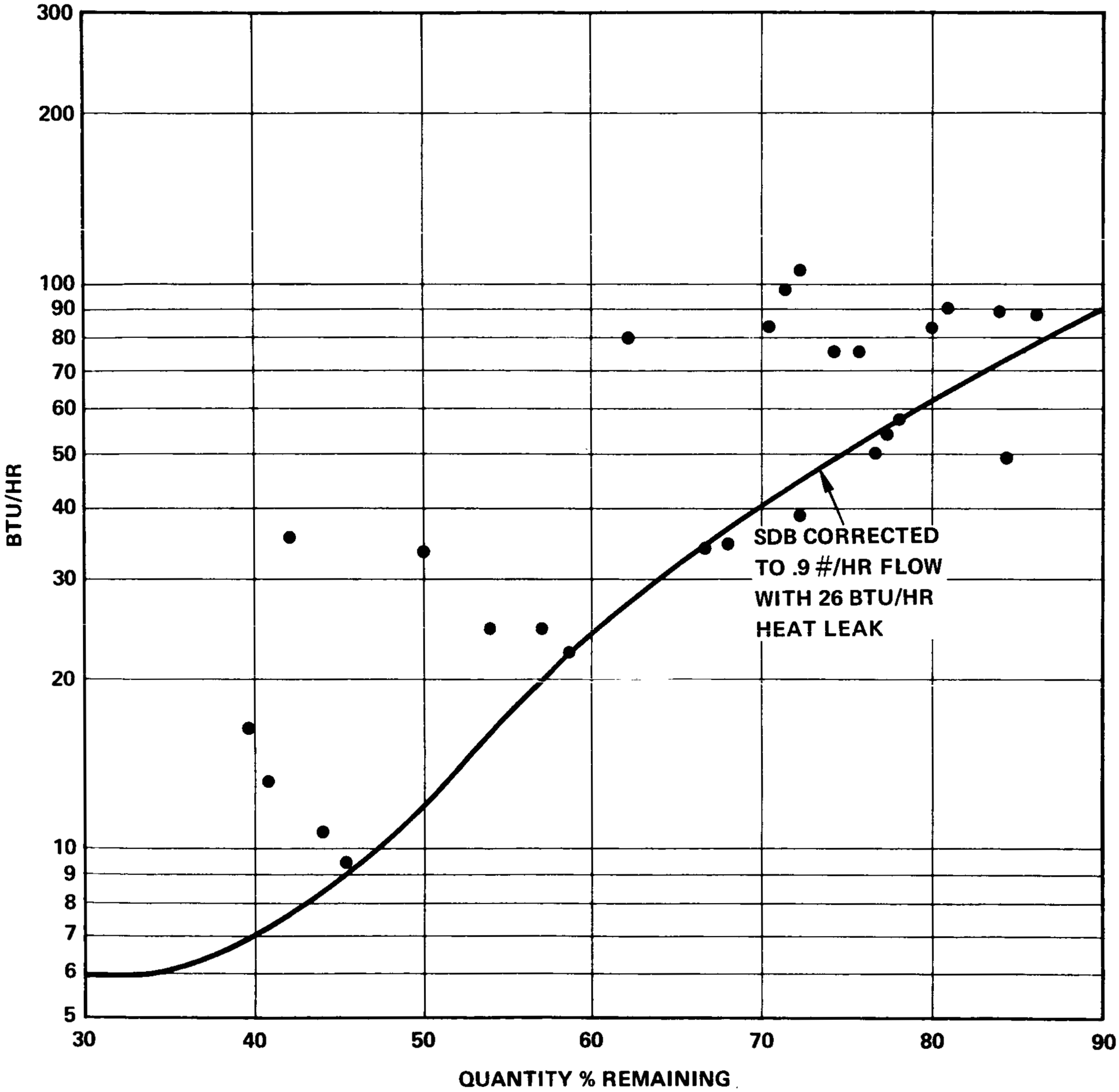
AVERAGE HEAT INPUT
APOLLO 9 O_2 TANKS

FIGURE 9



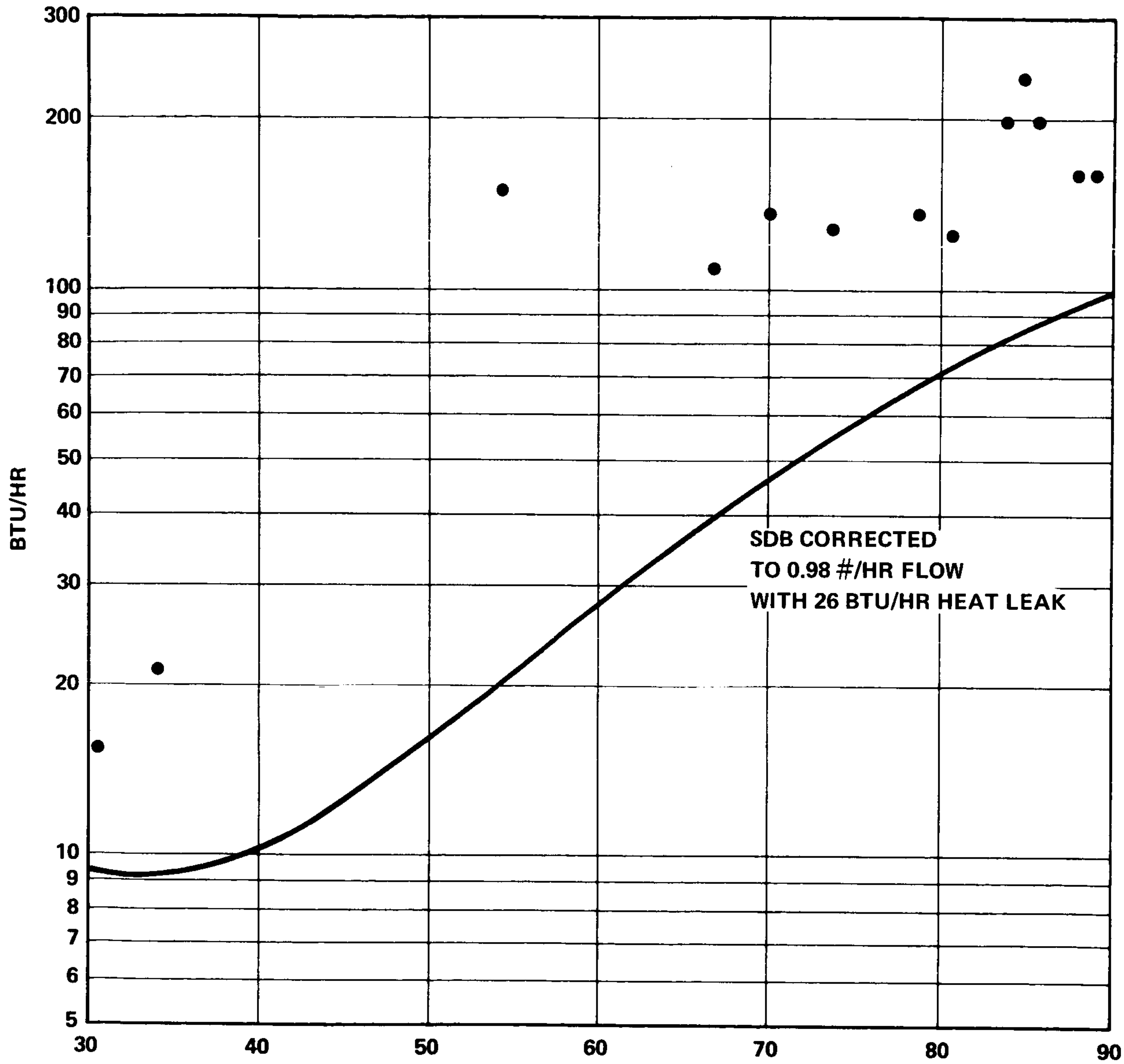
AVERAGE HEAT INPUT
APOLLO 11 O_2 TANK 1

FIGURE 10



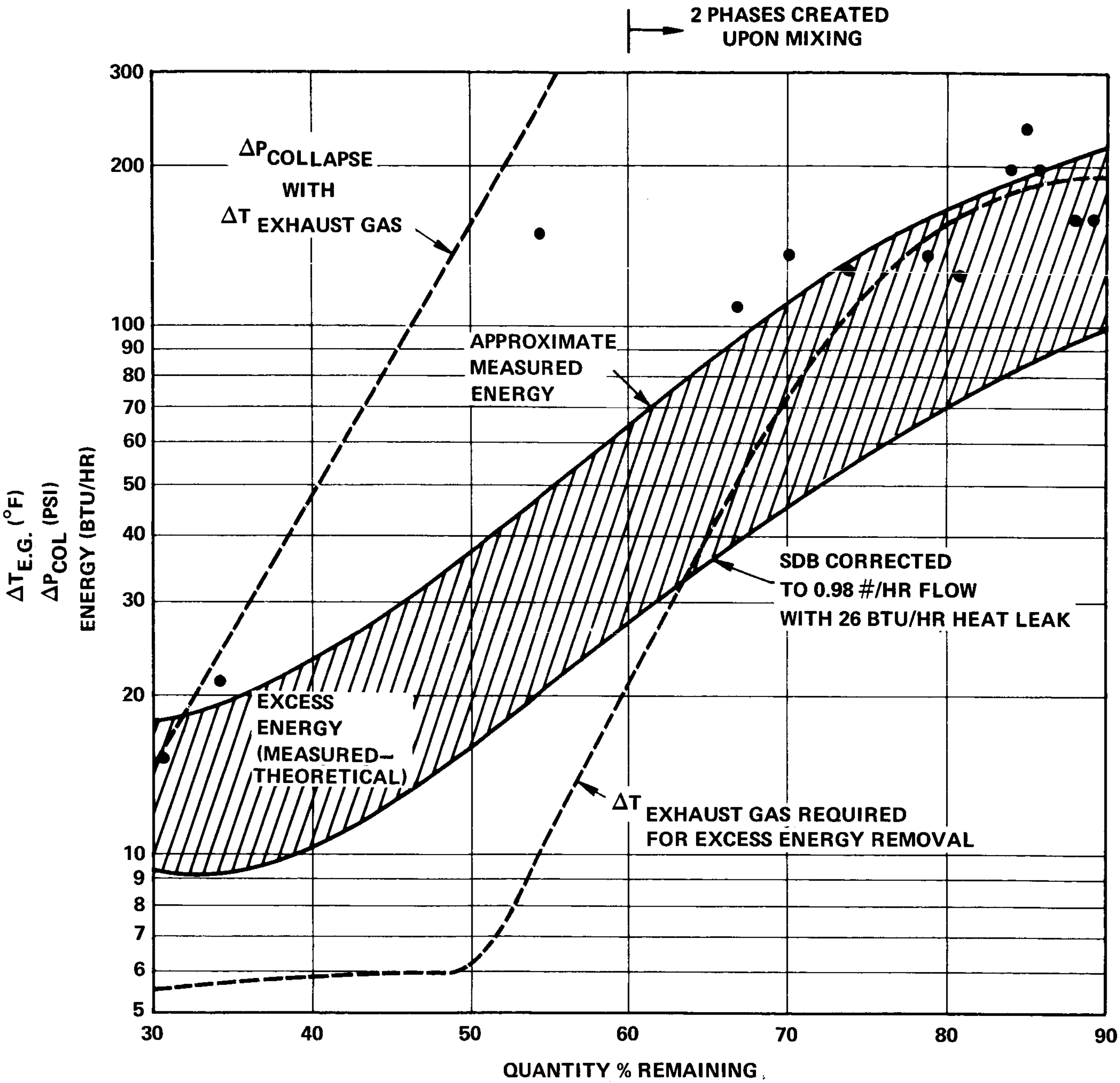
AVERAGE HEAT INPUT
APOLLO 11 O_2 TANK 2
(ONE HEATER FAILED)

FIGURE 11



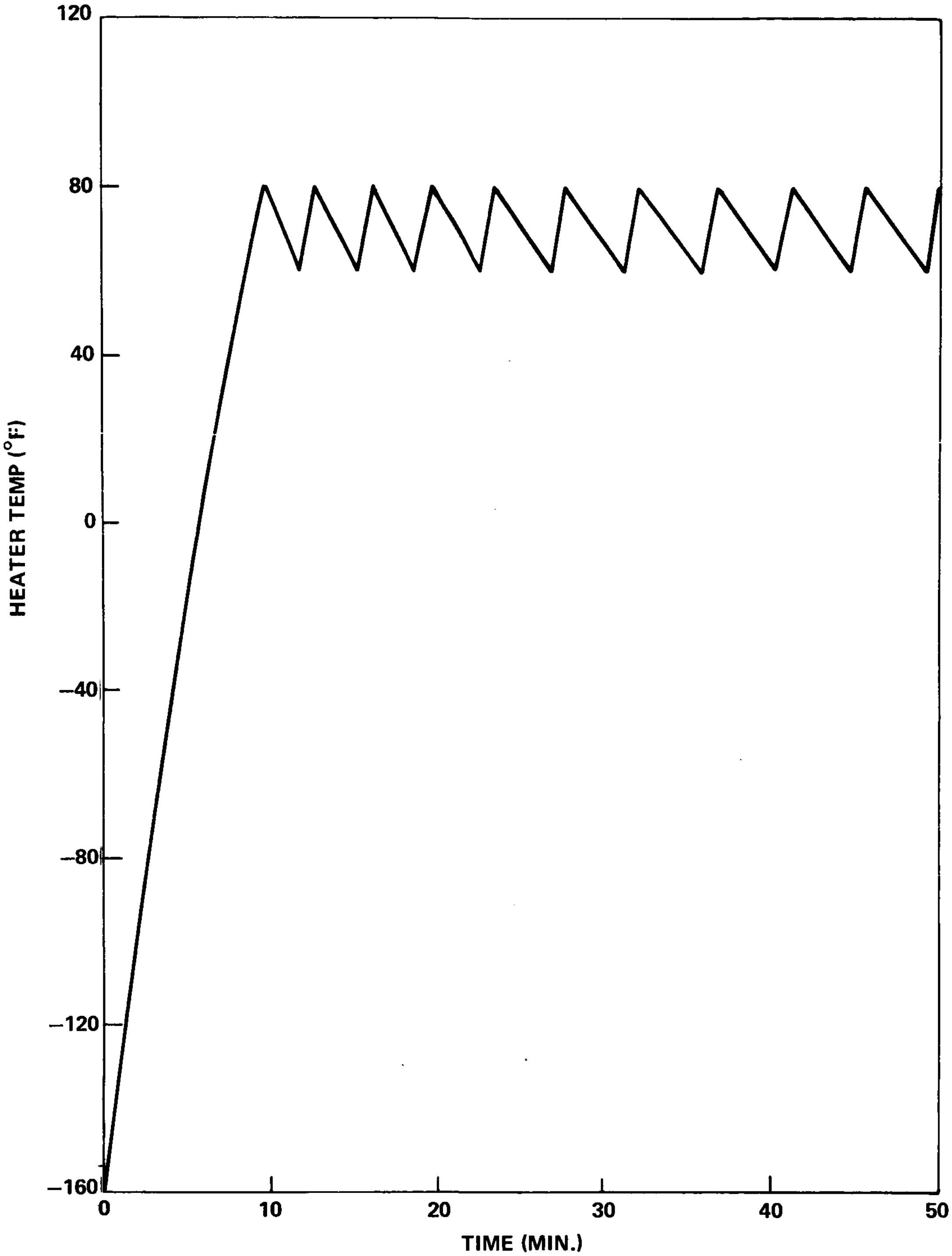
AVERAGE HEAT INPUT
APOLLO 12 O_2 TANKS

FIGURE 12



APOLLO 12 O_2 TANKS
EXHAUST GAS ΔT AND
POTENTIAL PRESSURE COLLAPSE
TO ACCOUNT FOR EXCESS ENERGY

FIGURE 13



HEATER TEMPERATURE VS TIME

HEATER INPUT: 114 WATTS (INTERMITTENT)

QUANTITY LEFT IN TANK: 20%

HEAT TRANSFER MODE: CONDUCTION TO OXYGEN
& RADIATION TO TANK WALL

FIGURE 14

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From: R. V. Sperry

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